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LEVELS OF BIM COMPLIANCE FOR MODEL HANDOVER

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SUMMARY: *The important process of design review, compliance checking and project handover information intake and processing have traditionally been paper based and manual tasks. These tasks are onerous and error prone. Moreover, they do not allow effective detection of design issues and validation of project information quality for handover which lead to waste of resources when performing maintenance and repairs during operations. Building Information Modeling has the potential to help owners overcome these challenges by enabling seamless exchange of project information between design, construction, and operations while supporting and proving opportunities for automated design reviews. However, this practice has yet to fully take root in the industry due to its relative novelty. The research project presented in this paper set out to understand how owners could adopt and implement BIM to support design and information handover review. Two large public owner organizations were investigated over five years to support this aim. The findings are articulated around three levels of compliance for the owner's project and BIM requirements. The findings on compliance review suggest three elements: model structure verification, model content verification and design compliance review. These three elements rely on model queries which are identified through investigation of owner's operational requirements. The presented research connects modeling practice to support facilities maintenance, owner's information requirements, and owner's design requirements and leverages this information for model based compliance review.*

KEYWORDS: *Building Information Modelling (BIM), Facilities Management (FM), compliance review, owner requirements, model handover.*

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1. INTRODUCTION

Building information modeling (BIM) is the digital representation of geometric and non-geometric facility information. It allows owners and project teams to leverage structured geometric and non-geometric project information to perform specific tasks and actions, and supports its reuse throughout an asset's lifecycle. As large owner organizations transition towards BIM-enabled project delivery and start requiring digital models as project deliverables to support their organizational practices, significant adjustments are required on both the part of industry actors and the owner organizations that commission work (Crotty, 2011).

While benefits for owners are increasingly being documented, the challenges in initiating and sustaining the transition to BIM are considerable (Eastman et al., 2011). Among others, establishing clear and coherent BIM requirements, adjusting internal practices and developing capabilities to process and manage BIM-enable project delivery are key in ensuring that the transition be successful. Furthermore, understanding which organizational practices need readjustment considering this transition to BIM is key in defining a trajectory for change (Kensek, 2015).

Among the many uses of BIM for owners, use of models to support automated handover of project information ranks consistently as highly desirable with automated review of design and compliance to technical and functional requirements slightly less important (Giel et al., 2015). These two uses in particular are seen as very important since, the latter helps an owner ensure he is getting the building he wants, while the former ensures he will be able to efficiently and effectively operate and maintain it while performing facilities management (FM) functions. According to International Facility Management Association (IFMA) FM is "a profession that encompasses multiple disciplines to ensure functionality of the built environment by integrating people, place, process and technology". There is still considerable work to be done to translate the potential uses of BIM for owners from theoretical propositions into tangible outcomes. For one, owners will need to be able to evaluate the fit of BIM and the use of models within their organisational contexts. If we take BIM-enabled design review and project information handover for instance, the evaluation process will entail checking for the compliance of the delivered models with owner's information requirements, to ensure that the required facility information is available in the models and that the model information is reusable within the owner's FM technology infrastructure. The new process requires a key element: a valid source of truth, ie. a well built and complete (to the necessary degree) BIM.

The objective of this research was to uncover and formalize the steps related with in-taking, processing and checking project information against a set of technical and functional requirements and translating them into a model-based workflow. The research project involved the study of two large owner organisations. Data collection involved analysis of project handover and FM documents, interviews with FM personnel, and investigation of project models from four major projects to identify model queries that can be leveraged for owners' BIM compliance review. A three-level approach to model-based compliance verification was developed from the findings and identified model queries. The three levels involve (1) **model structure verification**, which serves to identify any modeling issues that lead to miscomputation of, or impossibility to compute information from the model, (2) **model content verification**, which relates to ensuring the availability of the required geometric and non-geometric information in a model, and (3) **design compliance review**, which involves a set of computable queries that are developed from extensive analysis of owner requirements and that can be represented in, and queried from a project model. This approach informs areas of further investigation to extract and formalize computable queries for owners. The findings highlight the potential of model based project delivery that is compliant to modeling, information, and design requirements of owner organisations. The levels of compliance identified in this research suggest avenues to greatly increase the efficiency and effectiveness of project and project BIM review by owners to improve the quality of a facility, and the supporting information infrastructure to ensure it is properly run and maintained.

2. BACKGROUND

Major knowledge areas identified as being related with this research are the owners' design and project information reviews, and the use of BIM to perform design and project information reviews. These knowledge areas can further be broken down into model based reasoning (Korman et al., 2003, Nepal et al., 2012), rule checking and Industry

Foundation Classes (IFC are the open data format for openBIM) based reasoning (Zhang et al., 2013, Lee et al., 2016, Eastman et al., 2009), and building product models requirements (Kiviniemi, 2005). Design for FM focuses on making the right design choices for the efficiency of FM functions during operation. Compliance review focuses on ensuring that the design characteristics meet the owner requirements. Owner organizations require and manage a wide range of project information about their built assets. The variety of information is partly related to the O&M personnel within the same organisation who require different sets of information to perform the FM functions (Cavka et al., 2015). The analysis of owner requirements was part of another journal (Cavka et al., 2017) and can be accessed for more detailed information on categorization and content of owner requirements, and how these requirements relate to BIM enabled project delivery. The information needed for operations and maintenance was listed by Liu et al., 1994, Clayton et al., 1998, and Klein et al., 2012. Although literature focuses on listing required information during operations, this research analyses the owner requirements to identify required model information, and design conditions in order to use them during compliance review. Modeling for FM focuses on developing the required information content, and model structure. In terms of represented information in project models, Korman et al. (2003) use geometric characteristics (dimension, location) and topological characteristics of the components (components' spatial relationship in model) represented in a model based heuristic reasoning. However model based reasoning as described in Korman et al. (2003) does not include required component attribute information since it was developed for design coordination purposes. Emerging UK standards, such as PAS1192 and Level 2 requirements, are focused on the owner deliverable and they support the need for research, like this one, that bridge the owner requirements and handover models, and help improve managing compliance with such requirements. US National Institute of Building Standards (NIBS) BIM Guide for Owners has details relating to managing quality of owner data under the Managing Project Requirements and Deliverables section. The section introduces concepts related to quality planning, assurance, and control. Topics related to requirements capture, requirements formalization, and leveraging BIM for design reviews for compliance with requirements have been studied from different angels in the literature. Examples of barriers related to application of BIM based model checking (BMC) are unavailability of standardized procedure for converting design rules and regulations into digital rules, and large variation of how the designer is modelling and structuring information in the BIM software (Hjelseth, 2015). Hjelseth (2015) identified that the prescriptive rules could be directly converted into computable rules. Our research however uses both prescriptive and descriptive owner requirements that could be represented in and queried from a model. Statsbygg developed a digital rule set in Solibri Model checker for compliance checking with their BIM guidance (Hjelseth, 2015). According to Hjelseth (2015) the quality of the BIM file is of high importance for reliable model checking, and it is measured as the structure and content of relevant information, which is also in parallel with approach and findings of this research. During their investigation of model structure issues, Lee et al. (2015) investigated the warning messages to better understand the automatic detention of design related errors. Our research on the other hand relates such model structure issues with how they affect the accurate computation of the required information from the models. The IFC model quality test items identified in Lee et al. (2016) can be directly related to what is categorised as the model structure issues in our research. Eastman et al. (2009) describes work which focused on automating the design guidelines in a way that designs could be assessed and checked against specific criteria. Research in compliance checking and auditing mainly focuses on BIM enabled code checking (Choi and Kim, 2008). Others have parameterised the accessibility rules, mapped to their associated building objects and executed using Solibri Model Checker (Greenwood et al., 2010). Zhang et al. (2013) introduced a BIM-enabled, rule-based automated safety checking platform. A more recent study (Liu and Issa, 2014) was about leveraging BIM for maintenance accessibility problem detection using predefined rule sets in SMC during the design phase. However the work was limited to interference of other building objects with equipment's required service space. Our research on the other hand, leveraged identification and the use of equipment type specific maintainability characteristics, required information for maintenance as well as maintenance space interference for maintainability review. Liu and Issa (2014) mentioned "design requirements for maintenance friendly designs" which would have been created from an accumulated knowledgebase of situations that were encountered by maintenance personnel. However the knowledgebase was the result of specific conditions observed in buildings by solely the O&M personnel and, contrary to the method followed in our research, was not based on owner requirements documentation.

3. RESEARCH METHODOLOGY

The objective of this research is to uncover and formalize the steps related with in taking, processing and checking project information against a set of technical and functional requirements and translating them into a model-based workflow. We describe the methodology that we used to meet this objective in this section. Methodology can be summarized as; (a) investigate the set of owner requirements from two case studies, (b) define levels of compliance based on identified requirements, (c) identıfy and formalize those requirements that were deemed computable, (d) analyze digital models that were developed as part of the two case studies in the context of the computable requirements, and (e) validate applicability by using the identified computable requirements on models to review compliance and evaluate results with experts from the case organisation.

3.1 Sources of data collection

The research project involving the case study of two large owner organizations was conducted over a five-year period. The first case study involved a large Canadian university. The focus of this case study was put on the building operations department, which is responsible for the operations and maintenance of all non-residential buildings on campus. The department is responsible for 225 core university-owned buildings, with a total gross floor area of 810,119 m^2. The principal sources of data collected from the Canadian university were the organizational technical guidelines (the code of quality and performance for the design, construction and renovation of University-owned institutional buildings), FM applications and databases (to understand managed information in FM applications for asset management, maintenance management, facilities capital planning and management, records retrieval system), interviews with the FM personnel (to understand information and design requirements), and project data (such as project documents and models for two research buildings and a mixed use building- student residence and college). The second case study involved the agency responsible for delivering and maintaining public infrastructure for a provincial government in Canada. The agency is responsible for infrastructure planning, building and managing of government-owned infrastructure which includes health facilities, schools and other public infrastructure in the province. The agency is responsible for over 1,600 buildings, representing an approximate total gross floor area of 2,330,000 m2. The focus of the second case study was on the Capital Planning Division and the Properties Management Division. The principal sources of data collected from the provincial government body were Basic Master Specifications (BMS) that include sixteen divisions based on the MasterFormat, Organisational Technical Guidelines which includes technical design requirements for government owned facilities, Owners Statement of Requirements (OSR) which includes project specific requirements for a sample project, O&M applications and databases investigation to understand managed information (building and land information management system, facilities capital planning and management, facility maintenance systems, work order request tracking system, and a planning application), interviews with the FM personnel to understand information and design requirements, and project data analysis from project documents and models for a large institutional project.

3.2 Methods of data collection

While we investigated the organisational requirements through document analysis, we identified the undocumented personnel requirements through interviews, shadowing and performed walkthroughs with FM personnel. We conducted a total of 27 interviews with personnel from both organisations. The interviewed personnel from the Canadian university were from four departments (records, asset stewardship, operational effectiveness, utilities and energy) which were parts of two divisions (infrastructure development, and building operations). The interviewed personnel from the provincial government body were from four departments (project services, project delivery, technical services, and regional operations branches) which were parts of three divisions (capital projects, properties, and culture/ heritage). The interviews were designed to uncover each organisation's information landscape. Organisational technical requirements were analysed through investigation of both organizations' technical guideline documents. Project specific requirements were analysed through the owners' project briefs and statement of requirements documentation. Analysis of technology infrastructure of FM applications and databases was used for understanding managed FM information, information requirements for each FM function, and information structure. This information was used to help partly identify what model information was required, to what level of detail it should be developed, how it should be structured and in what format it should be exchanged.

Three projects' BIMs which were developed by different project teams were analysed for compliance using Revit, Navisworks, EcoDomus, SMC, and COBie format outputs of model content to uncover (a) modeling practices for elements such as definition of levels and spaces, defined relationships between model components, and nomenclature used (b) available geometric information, (c) available non-geometric information. The two out of three projects' BIMs were from the university case study and the third model was a large institutional project model from the provincial government case study. Since the investigated owners had not developed BIM requirements, nor did they have any internal BIM requirements, literature from sources such as National Institute of Building Sciences (NIBS), U.S. Army Corps of Engineers (USACE), Singapore BIM Guide, General Services Administration (GSA) National BIM Program, PennState BIM Planning Guide for Owners were analyzed to develop best practices and inform how requirements could be framed.

3.3 Method for model analysis

Intensive analysis on the two organisations' owner requirements and analysis of project models enabled identification of requirements that were later turned into computable requirements. In order to evaluate compliance, computable requirements were turned into model queries and were run on two project models using SMC. This process enabled identification of non-compliant model and design characteristics. Running queries on models helped validating the applicability of model based compliance verification, and design compliance review methodology. During the performed model analyses, we realized the significant model restructuring and manipulation that was required for preparing models for analysis from an owner's perspective. Such model manipulations were required to be able to accurately compute required information from the model. Yet often part of the managed information by the owner was not available in the models and it had to be manually entered if required. Once the model compliance was verified then design compliance review was performed using SMC. Design compliance review was also based on identified design characteristic requirements from the analysis of owner requirements. These requirements were used to identify the model queries that need to be run in order to identify non-compliant design characteristics that are contrary to the requirements. The project models were reviewed for compliance with owner requirements using the SMC rules that were based on the identified computable requirements. For this research SMC is used for performing the model based design compliance review. The advantage of using SMC is that it can use IFC version of a model to run rule based queries and identify non-compliance. In the following subsections, three levels of compliance review will be explained.

3.4 Method for validation

To validate the findings, the research team performed a review panel with domain experts. We asked these experts, three project managers from the Project Services Department, and a PM and a Maintenance Technical Specialist from the Building Operations for the large Canadian university, to evaluate whether the identified queries we developed from the set of identified computable requirements were representative of the information that is reviewed or checked during design reviews and at handover. We briefly explained the use of SMC to run the queries and how this process helped in identifying non-compliance to model and owner design requirements to the reviewers. We selected the experts intentionally from different departments and with different responsibilities in order to capture the varying perspectives on project delivery and FM practices within the context of a large owner organization. We based the validation of the identified queries on a five-point Likert scale. During the sessions, the experts were given a brief introduction of the research and what they were asked to rate. Information was then provided on the approach for evaluation of model and design compliance through predefined model queries. Feedback from the experts was requested at the end by opening the floor for a semiformal discussion, which provided insight into the use, and possible benefits of the introduced queries and process of using them.

3.5 Current practice

The analysis of the current project information handover and its review practices within the investigated owner organisations revealed that both organizations' involvement in any given project varied according to a project's delivery mode and the level of sophistication of the owner's employees in terms of design and construction knowledge. Both owners were actively involved over the projects' lifecycle in terms of design review across different disciplines. Indeed, staffs from both owners were tasked with reviewing design decisions to ensure that they comply with the owner requirements. These requirements cover a wide range of both formal (codes, design standards, organizational and project requirements), and informal (personnel requirements) requirements (H. B. Cavka et al., 2017). The reviewers would comment back to the project team with further requirements, suggestions and questions. In some instances, the project team would not incorporate these comments into the design, and a back and forth would ensue. Interestingly, reviewers would comment on the medium, the project documents such as plans and specifications, and highlight any inconsistencies and errors in the representation and the quality of information. The highlights of this portion of the research found that the design review process is a manual and time consuming one, and that it is mainly based on the reviewers' experience and knowledge rather than formalized review criteria. The vast quantity of information that must be processed by the reviewers in a short amount of time, leads to selective review which ultimately can result in a building that doesn't comply to the owner's requirements and needs.

Upon project completion, relevant project information is handed over to the owner to populate asset management databases and inform FM practices. We identified that the evaluation of the project's handover information poses a significant challenge for the owner, especially when it is completed near the end of the construction rather than as a gradual process throughout the project. The project information review process focused on the completeness of the document set (eg. the presence of a set of required documents), rather than the information content. For instance, on one of the investigated projects, one of the owners was provided with stacks of hardcopy drawings and documentation as well as a digital repository containing electronic versions of the documents. The set of information consisted of hundreds of individual PDFs, which included project drawings, manuals, and specifications. When the owners received the handover set there was no guarantee that the handover information was complete, or accurate which resulted in missing or erroneous data. Ultimately, we identified that upon project completion the owners lacked the time, resources, and technical knowledge to thoroughly evaluate the content of the handover set.

With regards to BIM-enabled project delivery, none of the owners that we investigated had defined information requirements for model based project and information handover. They did not know what to require in models, and how to require this information from the project teams. While it was expressed that they would like to validate completeness of the information in the handover models, they did not have the tools, expertise, or the resources to evaluate the models developed by the project teams. A significant issue that came up was that due to the unique nature of each project in terms of requirements, both owners were lacking detailed and formalized information requirement sets, and they did not possess the capacity for thoroughly evaluating design compliance according to the requirements that were in place. Moreover, due to the lack of specific BIM requirements, the project teams weren't modeling with automated review and compliance checking in mind, which effected correct computation of required information from models when required.

4. MODEL-BASED COMPLIANCE REVIEW

The model based compliance evaluation has the potential to improve to current compliance review process by providing the means for automation of compliance review, leading to reduction of errors compared to manual process, and providing owners with a method to evaluate the usability and quality of the models they receive. Three levels of compliance emerged from our analysis which are identified as being key for model-based project delivery (FIG. 1). We identified the required three levels of compliance as; compliance with the model structure requirements, model content requirements, and project requirements. Our analysis of project models indicates that each level is also a prerequisite of the next level to allow for the accurate query and computation of model information.

The first level involves the verification of a model's information and data structure to identify any modeling errors that lead to miscomputation and/or non-computation of model information. The second level is the model content compliance verification that involves validation of model information content against the owner's BIM requirements. This level ensures that the model content meets the owner's information requirements in terms of geometric and non-geometric content. The third level is the design compliance review where the design's fit with owner requirements is evaluated. The compliance review process for model content, structure, and design relies on tailored rule sets that originate from the owner requirements, and owner's current or potential model uses for FM. The compliance review methodology presented in this research accepts the model structure and content verification as a pre-requisite, and a part of the design compliance review from the model based delivery perspective. This approach is based on the model analyses performed during this research, which led to an understanding of issues related to current project models and current modeling practices of the project teams.

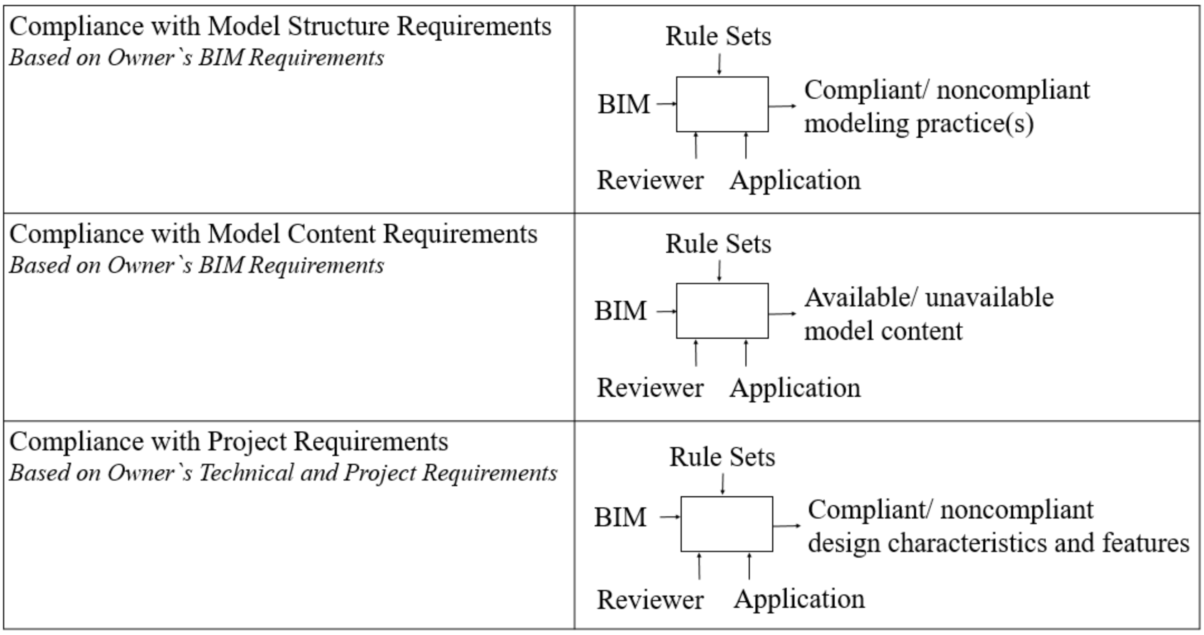

FIG. 1: Envisioned methodology for model structure and content verification, and design compliance review

The rule sets that are based on the computable requirements are used to execute model based structure and content verification and design compliance review. These requirements relate to FM requirements that are formalized in a model and therefore can be computed. Computable requirements cover the model structure and information requirements which enable information exchange between model and owner's FM application, and also the design conditions which enable efficient performance of FM functions. Identification of a model query originates from the analysis of owner requirements as explained in TABLE 1.

Such queries are later used to perform model based design compliance review. The methodology for identification of computable requirements, and turning these requirements into model queries is further explained in (Cavka et al., 2017). The analysis of owner requirements to identify model queries also supports the development of required FM model information. Because in order to be able to run the model queries, information that the queries are looking for should be made available in the models. In the context of this research project, these requirements were found embedded in formal owner requirements documents, and were also identified through interviews with FM personnel, analysis of owner organisations FM information databases, and analysis of best modeling practices that corresponds to the FM model uses. We base the analysis of best modeling practices on the research we performed BIM models using building information lifecycle management tools. Our investigation showed evidence to the required modeling practices that enabled the required information to be available and interpretable from the building model.

4.1 Model structure compliance verification

The intent behind model structure compliance verification is to ensure that the way in which the model is built is suitable for the getting the correct model information according to owner's requirements. Indeed, it is a given that a project BIM intended for FM use is modeled different from a design or a construction BIM. Our analysis of project models created for design, construction and (partly) FM uses also confirmed that the BIMs created for handover and FM use have a model structure that is different from the design and construction models. Modeled project information is structured according to the internal rules of the modeling application or the predefined rules for the IFC open format. Ensuring appropriate model structure entails modeling practices that are required (1) for computing required FM information correctly from a BIM, (2) for enabling information exchange between the model and the owner's FM applications. The analysis of the models for validation of structure compliance on the different projects led to identification of common and recurring issues in current modeling practice for design and construction phases that were not guided by clear BIM requirements. Fundamentally, the models analyzed, because they weren't structured properly, lead to miscomputation or unavailability of model data which was required for FM. The categorisation of identified modeling issues in this research that lead to categorisation of model structure issues as; representation and relationship issues related to spaces, components and systems, nomenclature and classification of equipment and systems, and coordination issues. The findings through model analysis highlight the need for the model to be checked for structural issues during model structure compliance verification before the information content and design compliance review can be performed. As a basic rule, SMC does prompt the user to accomplish certain tasks that relate to model structure compliance prior to performing any analysis.

TABLE 1: Computable query examples, query categorisation, and identified model queries to evaluate compliance with requirements

Computable Owner Requirement	**Model Query**
Main Floor Custodial Room near Loading Bay to be located very close to a loading bay	Find the spaces with the names custodial room and loading bay on the main floor Check whether the identified spaces are X distance apart
Emergency eyewash and or showers shall be provided in areas adjacent to areas where chemicals are used or stored appropriate for the hazard. According to ANSI / ISEA Z358.1-2014 the distance should be no more 55 ft.)	Identify eyewashes, showers, and labs in the model Check distances between components and spaces, whether the distance from an eyewash or a shower is greater than 55 ft.
Locate outside air intake louvers as far away as practical from all sources of contamination; avoid locating intakes at loading docks, fume hood exhausts, generator exhausts.	Identify air intake, loading docks and fume hood exhausts in the model Check if any air intakes are located at loading docks Check if any air intakes are located within X distance from fume hood exhausts

The examples of identified model structure issues are listed with examples from our analysis in TABLE 2 below. Undefined relationships between equipment, system, and spaces lead to not being able to identify the location of equipment, the system that equipment belongs to, and which space a system serves. Such information is required by the O&M personnel to perform their tasks. Room related modeling issues lead to miscomputation of space information, and in return miscomputation of such information as equipment locations. These issues were also listed as model related error messages by the modeling software as the models were opened for analysis. The identified error messages included; rooms without boundaries, multiple rooms in the same enclosed region, rooms not in properly enclosed regions, geometry cannot be created for a room, duplicate rooms, elements with duplicate number values, no space created for mechanical equipment, room tags outside of the rooms they belong to, and more than one space component in one space. Issues related to poor model coordination such as uncoordinated model elevations lead to derivation of inconsistent information from project models. Modeling errors, such as not connecting system components (i.e. air intake duct to an AHU) lead to not being able to identify all components of a system, and not being able to trace the system components between two points. Issues related to system and equipment nomenclature, such as not uniquely naming each component in a family, lead to problems with identification of number of available equipment of one type.

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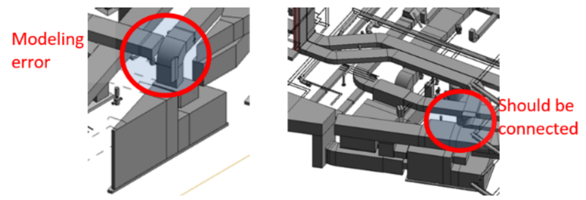
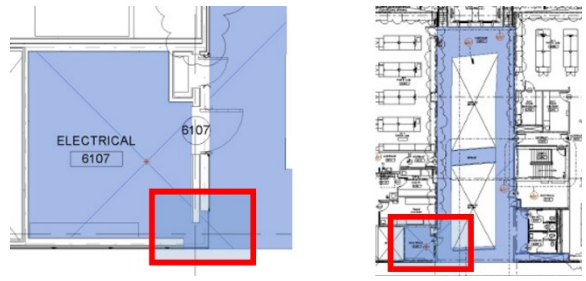
TABLE 2: Examples of identified model structure issues related to modeling practice

Modeling errors such as unconnected system components due to poor modeling. Such modeling errors affect computation of information; such as identification of systems and components that belong to a system.	
Modeling mistakes, like openings left in the walls, lead to miscomputation of room boundaries and effect definition of spaces. This leads to problems related to equipment being assigned to incorrect space information.	

Model structure issues identified from the analysis of project models were later turned into computable queries. These queries were run on models to review models for structure verification. TABLE 3 below contains examples of identified model structure queries and outcome of model analyses where the computable queries were used in the SMC application.

TABLE 3: Identified model structure requirements were turned into mode queries and were run on models using SMC rule sets to identify model issues

Requirement	**SMC model query**	**Model query outcome**
Accuracy of Room Boundaries	Solibri predefined rules: General Space Check – Space Properties – Space Dimensions Within Bounds And/or Solibri predefined rules: General Space Check – Space Location – Space Validation	*University campus building* Boundary Inaccuracy: 47 spaces *Provincial government building* Boundary Inaccuracy: 176 spaces
Defined Space-Asset Relationships	Take off the attribute 'Relation' – 'Nearest Space' in Solibri ITO, get the number of components with and without 'Nearest Space' value	*University campus building* Total number of components in mechanical model: 5864 Number of components that belong to spaces: 4904 (83.63%) *Provincial government building* Total Number of Components being checked in mechanical model: 39268 (Rows Exceeds the Maximum Value) Number of components that belong to spaces: 28774 (73.28%)
Intersecting spaces	Solibri predefined rules: General Space Check – Space Location – Space Intersections	*University campus building* Intersection: 10 places *Provincial government building* Intersection: 61 places

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4.2 Model content compliance verification

The intent of the model content compliance verification stage is to evaluate the quality of information contained within the model. This ensures that the information contained in the model is fit for use to support handover and FM functions. Among other things, a model intended for FM use requires specific geometric, and non-geometric information to populate the owners FM databases and to help the performance of FM functions. The issues related to model content that were highlighted in this research are the missing geometric and non-geometric information compared to information required (1) by the owner, (2) for performing FM functions, (3) for exchanging information with owner's FM databases, and (4) for model-based compliance review. The different dimensions of information quality include missing model geometry, system, and space representations, and representation of how these relate to each other as well as missing non-geometric information relating to specific attributes found in a model. TABLE 4 includes examples of identified model content issues during our analysis of project models.

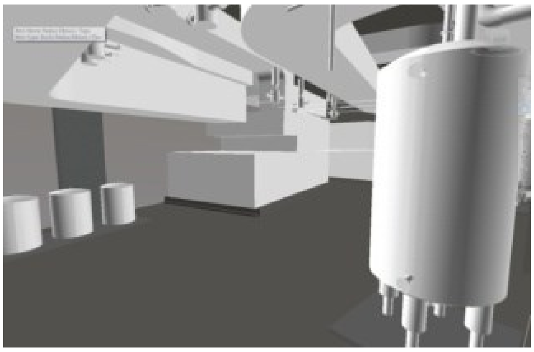
TABLE 4: Examples for missing geometric, and non-geometric project information identified with model content

Missing Geometric Information

Representation: component and system representation

Identification of missing geometry through comparison of as-build and model representation: most of plumbing is not represented, electrical control panel is not represented, number of expansion tanks are misrepresented

As built mechanical room



Model information

Missing Non-geometric Information

Attributes: component, system, and space attributes

Required Information	**Model Information**
Division 15_15130 Pumps_3.4 Pump schedule	**Available:** Manufacturer, Model, Size
Pump label, Location, Service, Manufacturer, Model, Size, Capacity L/s, Minimum pump Efficiency, Motor kW, Motor efficiency	**Not available:** Label, Location, Service, Capacity, Minimum Pump Efficiency, Motor, Motor Efficiency **Mechanical parameters:** the attribute efficiency is defined but no value was entered **Electrical parameters:** the motor attribute is defined but no value was entered

4.3 Design compliance review

Once the structure and the content of a model have been validated, it is then possible to check project model for compliance to design requirements, including technical, functional, aesthetic and operational. The intent at this stage is to identify non-compliant design characteristics and design features that are contrary to the owner requirements. During the analyses of project models design characteristics that were contrary to the Technical

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Guidelines, owner statement of requirements (OSR) document, and O&M personnel requirements (in the areas such as maintainability, accessibility, compliance with space and area requirements etc.) were identified. The example of the mechanical room in the University campus, which was mentioned as being one of the most cramped and problematic mechanical rooms on campus, is a good case in point. The technical guidelines for the university clearly stated that "no mechanical room will be accepted with poor and difficult access for maintenance", "all plumbing equipment requiring frequent maintenance to be readily accessible", and "do not locate plumbing equipment at ceiling height, requiring scaffolds, ladders, removal of other equipment". However the pumps in this room were installed on the ceiling, and they were buried under a maze of pipes which make it difficult for the maintenance personnel to access the pumps for maintenance. For maintenance or repair, crews would need to remove other components, and need to use extra tools (like ladders and lifts) to remove the pumps that were installed at the ceiling height. Model queries were developed from this particular example for evaluating pump locations in a design for compliance with owner requirements. In this case, the researchers had to define requirements such as "poor and difficult access for maintenance", "being readily accessible" in a computable way that would work with project models. On the other hand developing model queries for such requirements as identifying "pumps located at ceiling height" were relatively simple using SMC rule sets.

As another example, for the provincial government body and the project that was studied, the owners statement of requirements (OSR) stated that the "emergency eyewash and or showers shall be provided in areas adjacent to areas where chemicals are used or stored appropriate for the hazard". As a requirement the distance between a lab and an emergency eyewash & shower was determined to be no more 10 seconds' walk or 55 feet (16.76 m) according to ANSI/ISEA Z358.1-2014. By using the owner's requirement and the related standard, a model query was created. When the query was run on the model using SMC, the output of the model query showed that all the labs, except for one, were with proper eyewashes at the required distance. One lab was identified as being too far from the emergency shower.

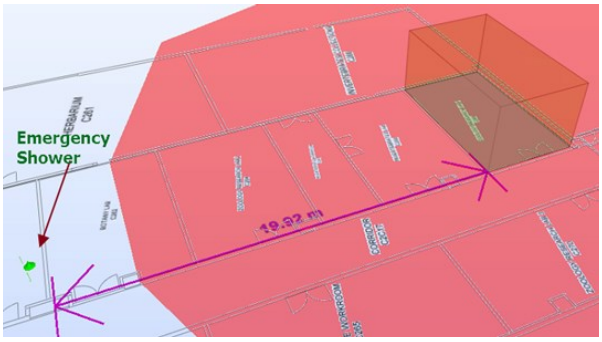


FIG. 1: Running model queries that were based on the OSR helped identifying non-compliant design characteristics such as distance from the lab to the closest emergency shower

TABLE 5 exemplifies the identified computable requirements from the owner requirements and used model queries for design compliance review.

TABLE 5: Identified computable queries from the owner requirements were turned into model queries which were later run on models using Solibri Model Checker (SMC) to evaluate design compliance

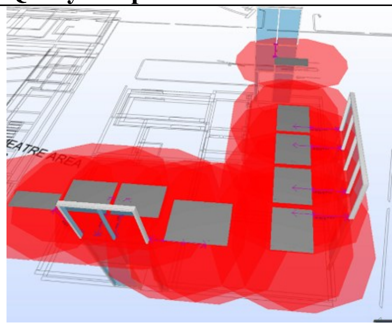
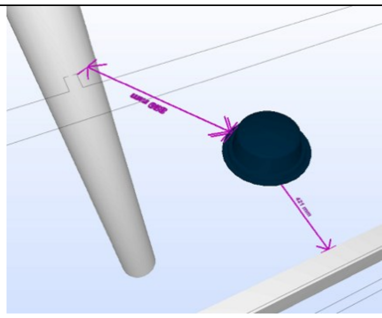
Owner Requirement	**Model Query in SMC**	**Query Output**
Radiant heating panels shall not face windows	Used SMC Rule 222 The minimum 2D distance between radiant panel and window is approximately 7 ft	
Drains should not be near beams and columns	Used SMC Rule 222 4' is used as the minimum required distance between drains and structural beams and columns	
Electrical rooms are preferred to be located on North or East exterior wall	Filter Rooms with Name of 'Electrical' or 'Elec' and observe the location using SMC	*University building model* Electrical Room Number: 1 Location on North or East exterior wall: 0 *Provincial Government Building* Electrical Room Number: 13 Located on North or East Exterior Wall: 9

TABLE 6 is a list of design characteristics that influence the performance of FM functions which were identified during the investigation of owner requirements. The design characteristics are the results of design decisions and they are represented in project artifacts. BIM's potential, as a project artifact in model-based project delivery, to be used for reviewing and evaluating a design for such characteristics, was demonstrated in the research by running identified queries on the project models. The accessibility and maintenance information categories in the table have overlaps with previous literature about maintenance and maintainability categorizations. However the computable requirements categorization as a whole and the complexity, standardization, and spatial requirements categories are mainly the results of this work.

TABLE 6: Categorisation of identified computable requirements which were used for model based design compliance review

Requirement Category	Requirement Subcategory	Design criteria and information to be reviewed
Complexity	Aggregation	Variety components within a system
	Composition	Scatter level of systems' components throughout the building
	Design complexity	Variety and # of complicated building systems
		Crowded mechanical rooms
	System complexity	Interdependencies between systems
		# of systems working together
Accessibility	Access for maintenance	Access to equipment or its parts
	Visual access	Clear line of sight to equipment for visual inspection purposes
	Disassembly from location	Ease of removal, replacement
	Removal from the room/building	
	Installation requirements	For different equipment types (e.g. height & installation surface for pumps)
	Access to mechanical rooms (influence travel time/ distance)	Layout of mechanical rooms
		# of mechanical rooms
		Closeness of mechanical rooms to each other
		Elevator access to rooms
Standardisation	Equipment variety	Within the building and amongst the campus buildings (building & campus scales)
	Parts availability	
Maintenance Information	Required information from asset databases, user requirements, and manuals & specs	Maintenance schedules/times
		Maintenance frequency
		Instructions for maintenance tasks
		Identification/ Tagging
	Required attributes	Performance information
		Required maintainability attributes for equipment types (e.g. maintenance frequency and weight for pumps)
Spatial requirements	Proximity	Component to component proximity
		Component to space proximity
		Space to space proximity
		Component to building perimeter proximity
		Component to building elevation proximity
	Adjacency	Space to space adjacency
		Access from space to space
	Relationship	Conflicting component-space relationships

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5. VALIDATION OF IDENTIFIED AND USED MODEL QUERIES

The validation of the research is based on the representativeness of the used queries. The identification of the queries is based on the investigated organisations' formalized requirements, requirements from analysis of the performed interviews with the FM personnel, and owner's BIM requirements from the literature. In this sense validation of the queries is already supported by the grounded research approach, which is based on actual cases and requirements from two large owner organisations. In order to validate the representativeness of the queries five experts from the investigated organisations were asked to rate the list of queries from not representative to highly representative. A five level evaluation scale was used for the degree of representativeness of each query; query is always, often, rarely, never used for compliance review, or non-applicable for the queries that are not part of the expert's knowledge area. 87 queries related to 37 design conditions, information requirements, and model requirements were evaluated for representativeness. The queries were related to architectural and mechanical designs. More specifically the queries covered information such as architectural area/ space/ room components and attributes, mechanical and plumbing system/ equipment/ component attributes, location and serviceability. The results were 72% of the identified computable queries in this research were representative of the "always" (42%) and "often" (30%) used queries that the experts would use when they evaluate handover information compliance to the owner requirements. According to the interviewed experts, being able to use such queries during design evaluation on a BIM would potentially help identify non-compliant design characteristics wıth improved accuracy for the investigated institution. 20% of the identified computable queries were representative of the "rarely" used queries, and 8% of the identified computable queries were not as part of the queries that the experts would use during compliance reviews. The completeness of the identified queries was not validated since the owner requirements cover a wide range of building components and systems. It was not practical or feasible for the period of this research to gather a complete set of queries, for a complete set of building systems that an owner would require in a project. This was also not practical since the set of requirements are updated too often by owner organisations. According to one interviewee, the current version of the Technical Guidelines may become outdated by the time someone prints them out from the organisation's web site.

6. CONCLUSION

While the use of BIM is becoming more common during design and construction phases of a project, many owners still lack the knowledge and motivation to leverage BIMs throughout the facility lifecycle. The challenge facing owners undertaking the BIM adoption and implementation process are multiple. Organizational considerations, including staffing and training are front and center. This research looked at the technical challenges associated with this transition. Mainly, we understand that the way in which owners ask for BIM on their projects will have repercussions across their assets' lifecycles. This research developed a three level approach for model-based compliance review of project information. We identified that in order to support the different uses of BIM by an owner, there is a need to: (1) ensure project models are structured properly and consistently, and (2) the information contained in the model is accurate, complete and reliable. The third step involves design compliance review which can take on many different meanings for an owner; in this case it is compliance of design to support effective FM practices. The main challenges with this are to develop a clear set of information requirements, and developing the expertise and tools to evaluate compliance of consultants' models with these requirements. This research exemplified and categorised current model content and structure issues identified from the analysis of four project models. In terms of model structure compliance review, the contribution of the research is that the determined model issues, which are also identified in previous research, are shown to have direct effect on the computation of required information, and in its reuse for FM. A process for compliance review is presented, and queries that can be represented or performed in a model for design compliance evaluation are categorised. An analysis of owner requirements is used for identification of such computable requirements. A subgroup of organizational requirements that can be turned into computable queries are categorised for model based design compliance review. During the review process the queries that are developed from the identified computable requirements were run on models using SMC, to compare the digital representation of the project model with the owner requirements. This allowed for automatically uncovering discrepancies in the proposed designs of the various projects studied, a process that can save owner's significant amounts of time and help them ensure that they obtain designs that suit their needs. We expect that this research would help owners understand how to identify model requirements, and how to review the compliance of the handed over models according to information, FM specific modeling, and finally design requirements. Currently identified queries however are not adequate for a complete project review process. The number of queries and the coverage of building systems and components should be improved as a recommendation for future research in this area. Usability studies involving the owners' personnel applying the identified queries on project models are also recommended. Such studies would help understand required expertise for using the BIM tools, and interpretation of model query results by the owners' FM personnel.

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